shoppers are still more likely to make snack food choices based on taste rather than health benefits. For many consumers snacks remain a means of satisfying an immediate hunger and are not viewed as an opportunity to obtain needed nutrients. This apparent dichotomy between consumer expectations and their actual demands is a challenge constantly faced by food processors, and research is increasingly being focused on developing snack foods that taste good, promote satiety, and provide a “nutritional nudge,” rather than an all-out push to maximize nutritional benefits that can lead to product failure (30).

Even with ongoing efforts by the industry, the general consumer perception of food processing is that it may be important for convenience and extended shelf life but that it is not a means of promoting health. Just the same, a huge opportunity exists to develop foods that provide not only the essential nutrients needed for life but also other bioactive compounds that can promote health and help prevent disease. Epidemiological studies have consistently shown that diet plays a major role in the prevention of chronic diseases. Consumption of fruits, vegetables, and grains is strongly associated with reduced risk of ailments such as cardiovascular disease, certain cancers, and diabetes (16). This is underscored in the 2010 Dietary Guidelines Advisory Committee (DGAC) report, which suggests certain health outcomes, such as protection against cancers, can be promoted by consumption of at least 5 servings of fruits and vegetables daily (25). Furthermore, the low caloric density of fruits and vegetables is an important tool in energy balance and weight management, which also bring about various health benefits. The DGAC report also mentions that despite the known benefits of fruits and vegetables, intake of this food group in the United States is consistently below recommended levels. Average consumption is <50% of the recommended intake for fruits and <60% of the recommended intake for vegetables. Although the DGAC report calls for minimal processing of fruits and vegetables, it also advocates the engagement of academia and industry in changing the food environment. Technological innovations in the use of fruits and vegetables and their incorporation in ready-to-eat products such as snacks and breakfast cereals may offer a route for increasing their consumption. Thus, food processing can contribute to consumer health, and this needs to be communicated effectively to the wider public.

S. Alavi
Department of Grain Science and Industry, Kansas State University Manhattan, KS, U.S.A.

F. Giannetta
Danone Group
Lyon, France

A. Nanjundaswamy
Department of Agriculture, Alcorn State University Lorman, MS, U.S.A.

R. Madl and P. Vadlani
Department of Grain Science and Industry, Kansas State University Manhattan, KS, U.S.A.

Is “healthy snack” still an oxymoron? As more consumers try to follow a “healthier” diet, the food processing industry is becoming more sensitive to the delivery of products with nutritional benefits. The reality is that despite their good intentions delivery of Antioxidants through Fruits and Vegetables in Extruded Foods
Delivery of Fruits and Vegetables Using Extrusion Processing

Extrusion is an important food processing technology and adds immense value to grain-based raw materials ranging from corn, wheat, and rice to sorghum, oats, and soybeans. Extruded products comprise a multibillion dollar market in the United States alone and include foods such as breakfast cereals, savory snacks, pastas, confectionery, and texturized vegetable proteins, as well as products for animal consumption such as pet foods and aquatic feeds.

In recent years, research has been focused on utilization of extrusion for production of nutritious processed foods. The versatility of extrusion and its inherent economies of scale and process efficiency make it a highly viable technology for delivery of enhanced nutrition. The addition of fruits and vegetables to extruded products has been studied extensively, and the use of by-products from fruits and vegetables in extruded foods is a growing trend in the literature (2,5,17,20,31). One motivation for the use of fruit and vegetable by-products is the value added to food processing residues and reduction of waste (32). Other drivers are the concentrated nutrient contents of such by-products (especially in terms of bioactive compounds) and growing interest in increasing the dietary fiber content of many foods (18,19,21).

A previous article published in Cereal Foods World by our research group described the use of extrusion for inclusion of fruit fiber in expanded snacks and provided a systematic understanding of the process dynamics, cellular architecture, textural properties, and consumer acceptance of high-fiber products (1). Despite the information available on the effects of added fruits and vegetables on the quality parameters of extrudates, their nutritional properties, including the retention and antioxidant activity of bioactives and phytochemicals, have not been studied in much depth. This article focuses on these important aspects.

Incorporation of Apple and Tomato Pomaces in Extruded Products

Apple pomace is a by-product of the apple processing industry and consists of dried and ground peels and cores. The typical composition is 51–90% total dietary fiber, 2–7% protein, 2–4% fat, and ≤2% ash (7,23). Apple pomace has a high total phenolic content and antioxidant activity, which, along with its high fiber content, is the main reason it has been studied extensively over the past few years as a potential food ingredient (6,15,22,23,28,29). Similarly, tomato pomace is a by-product of commercial processing. Tomato pomace consists of 44% seed and 56% pulp and skin and has an average composition of 59% fiber, 26% sugars, 19% protein, 8% pectin, 6% fat, and 4% minerals (8,14). Tomato pomace typically has a high concentration of carotenoid compounds such as lycopene and β-carotene, primarily from the skin (14,26).

The apple pomace used in the current study consisted of 63% total dietary fiber (47% insoluble and 16% soluble), 9% protein, and 5% fat, whereas the tomato pomace consisted of 59% total dietary fiber (50% insoluble and 9% soluble), 21% protein, and 17% fat. Blends were formulated with whole soft wheat flour, tomato or apple pomace, and pregelatinized starch (an expansion aid) in ratios of 90:0:10, 75:15:10, and 60:30:10. These ratios corresponded to 0% (control), 15%, and 30% pomace levels, respectively, with the aim of delivering 4, 6, and 8 g of total fiber/30 g serving of final product. Each blend was hydrated to 18% moisture (wet basis).

Table I. Concentration of phenolic compounds (μg/g) in whole soft wheat flour, apple pomace, and tomato pomace

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Ferulic Acid</th>
<th>Caffeic Acid</th>
<th>Coumaric Acid</th>
<th>Chlorogenic Acid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole wheat flour</td>
<td>14</td>
<td>56</td>
<td>65</td>
<td>0</td>
</tr>
<tr>
<td>Apple pomace</td>
<td>1,160</td>
<td>402</td>
<td>4,758</td>
<td>964</td>
</tr>
<tr>
<td>Tomato pomace</td>
<td>60</td>
<td>333</td>
<td>227</td>
<td>954</td>
</tr>
</tbody>
</table>

Table II. Concentration of phenolic compounds (μg/g) in extruded products and unprocessed blends containing apple pomace

<table>
<thead>
<tr>
<th>Product†</th>
<th>Ferulic Acid</th>
<th>Caffeic Acid</th>
<th>Coumaric Acid</th>
<th>Chlorogenic Acid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unproc. control</td>
<td>12.6</td>
<td>50.4</td>
<td>58.5</td>
<td>0</td>
</tr>
<tr>
<td>Unproc. 15% apple</td>
<td>184.5</td>
<td>102.3</td>
<td>759.4</td>
<td>144.6</td>
</tr>
<tr>
<td>Unproc. 30% apple</td>
<td>356.4</td>
<td>154.2</td>
<td>1,460.4</td>
<td>289.2</td>
</tr>
<tr>
<td>LT control</td>
<td>6.0</td>
<td>21.0</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>LT 15% apple</td>
<td>109.5</td>
<td>75.5</td>
<td>412.5</td>
<td>0</td>
</tr>
<tr>
<td>LT 30% apple</td>
<td>246.0</td>
<td>84.0</td>
<td>1,019.5</td>
<td>93.5</td>
</tr>
<tr>
<td>HT control</td>
<td>10.0</td>
<td>18.0</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>HT 15% apple</td>
<td>118.5</td>
<td>75.0</td>
<td>467.0</td>
<td>0</td>
</tr>
<tr>
<td>HT 30% apple</td>
<td>236.5</td>
<td>82.0</td>
<td>1,008.0</td>
<td>43.0</td>
</tr>
</tbody>
</table>

† Unproc. = unprocessed blend; LT and HT = low- and high-temperature extrusion, respectively.

Table III. Concentration of phenolic compounds (μg/g) in extruded products and unprocessed blends containing tomato pomace

<table>
<thead>
<tr>
<th>Product†</th>
<th>Ferulic Acid</th>
<th>Caffeic Acid</th>
<th>Coumaric Acid</th>
<th>Chlorogenic Acid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unproc. control</td>
<td>12.6</td>
<td>50.4</td>
<td>58.5</td>
<td>0</td>
</tr>
<tr>
<td>Unproc. 15% tomato</td>
<td>19.5</td>
<td>92.0</td>
<td>82.8</td>
<td>143.1</td>
</tr>
<tr>
<td>Unproc. 30% tomato</td>
<td>26.4</td>
<td>133.5</td>
<td>107.1</td>
<td>286.2</td>
</tr>
<tr>
<td>LT control</td>
<td>6.0</td>
<td>21.0</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>LT 15% tomato</td>
<td>0.0</td>
<td>93.0</td>
<td>65.0</td>
<td>37.0</td>
</tr>
<tr>
<td>LT 30% tomato</td>
<td>32.0</td>
<td>17.03</td>
<td>23.0</td>
<td>202.0</td>
</tr>
<tr>
<td>HT control</td>
<td>10.0</td>
<td>18.0</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>HT 15% tomato</td>
<td>27.0</td>
<td>88.0</td>
<td>53.0</td>
<td>65.0</td>
</tr>
<tr>
<td>HT 30% tomato</td>
<td>23.0</td>
<td>118.0</td>
<td>64.0</td>
<td>0</td>
</tr>
</tbody>
</table>

† Unproc. = unprocessed blend; LT and HT = low- and high-temperature extrusion, respectively.

Table IV. Concentration of carotenoids (μg/g) in extruded products and unprocessed blends containing tomato pomace†

<table>
<thead>
<tr>
<th>Product†</th>
<th>Lycopene</th>
<th>β-Carotene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unproc. 15% tomato</td>
<td>9.4</td>
<td>14.3</td>
</tr>
<tr>
<td>Unproc. 30% tomato</td>
<td>18.9</td>
<td>28.6</td>
</tr>
<tr>
<td>LT 15% tomato</td>
<td>6.0</td>
<td>3.5</td>
</tr>
<tr>
<td>LT 30% tomato</td>
<td>16.1</td>
<td>12.1</td>
</tr>
<tr>
<td>HT 15% tomato</td>
<td>5.5</td>
<td>0.0</td>
</tr>
<tr>
<td>HT 30% tomato</td>
<td>12.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

† Concentration of lycopene and β-carotene in unprocessed tomato pomace was 62.9 and 95.4 μg/g, respectively. No carotenoids were detected in extruded controls (0% pomace).

b Unproc. = unprocessed blend; LT and HT = low- and high-temperature extrusion, respectively.
 incorporated in whole wheat-based expanded products using extrusion without negatively impacting overall expansion, and pomace addition at any level favored longitudinal expansion at the expense of radial expansion. A higher extrusion temperature reduced mechanical energy input, probably due to lower melt viscosity, but the increased thermal energy had the net effect of moderately improving overall expansion.

Antioxidant Profiles of Pomace Blends Before and After Extrusion

Phenolic compounds were extracted from raw materials and extruded samples using 80% methanol and shaking for 2 hr in the dark. To quantify carotenoids, extraction was performed by grinding samples in a mortar with acid-washed sand (40–100 mesh size) and dichloromethane solvent. The final step in the extraction process was centrifugation. The resultant supernatants were analyzed by high-performance liquid chromatography (HPLC) to identify and quantify the antioxidants. An HPLC system (LC-20, Shimadzu) equipped with an auto sampler, 150 mm × 4.6 mm C18 column (Prodigy, Phenomenex), and photodiode array detector with the appropriate mobile phase for phenolic compounds and carotenoids was used.

Four phenolic compounds were identified in whole soft wheat flour, apple pomace, and tomato pomace samples: ferulic, caffeic, coumaric, and chlorogenic acids (Table I). The phenolics in wheat are chiefly present in the outer bran layers and vary greatly depending on cultivar, with some cultivars having total phenolic contents that are much higher (1,000–5,000 µg/g) (4,10) than the contents reported in the current study. The two pomaces were far richer in phenolic compounds than the wheat flour, and the latter did not contain any chlorogenic acid. Apple pomace contained ≈20 times more ferulic acid (1,160 µg/g) and coumaric acid (4,738 µg/g) than tomato pomace (60 and 227 µg/g, respectively). The concentration of caffeic acid also was ≈20% higher in apple pomace, while chlorogenic acid was about the same in both pomaces. In addition, two carotenoids were detected in tomato pomace (but not in apple pomace or wheat flour): lycopene (63 µg/g) and β-carotene (95 µg/g).

The same antioxidants also were identified in extruded products, and their concentrations were compared with those in unprocessed blends, as calculated from individual ingredients (Tables II–IV). It was obvious that extrusion caused a reduction in concentrations of both phenolic compounds and carotenoids. Chlorogenic acid and β-carotene were the most susceptible to extrusion, especially at higher process temperatures. Degradation due to thermomechanical treatment during extrusion might be one reason for the loss of detectable antioxidants and was anticipated. However, antioxidant activity data were surprising (discussed below).

Free-Radical Scavenging Capacity

Free-radical scavenging capacity or antioxidant activity is a better measure of the
effectiveness of antioxidants in foods than is concentration. The DPPH method, as described by Beta et al. (4), is a common technique for measuring antioxidant activity and was employed in the current study. It involves the use of the free radical 2,2-diphenyl-l-picrylhydrazyl (DPPH) as a standard for evaluating the scavenging capacity of antioxidants in a methanol solution. In its radical form, DPPH absorbs light at a wavelength of 515 nm, but the absorption disappears upon reduction by antioxidant species, leading to discoloration. Antioxidants were extracted from raw materials and extruded samples using methanol. The extract subsequently was reacted for 30 min with DPPH solution ($6.10^{-5}$ M in methanol) in the dark. Methanol was used as the blank or control. Scavenging capacity ($I$) was calculated as percent discoloration as follows:

$$I(\%) = \left(1 - \frac{A_{515 \text{control}}}{A_{515 \text{sample}}} \right) \times 100$$

where $A_{515 \text{control}}$ is the absorbance of the control at time = 0 min and $A_{515 \text{sample}}$ is the absorbance of the sample at time = 30 min. Scavenging capacity data were converted to antioxidant activity, expressed as ascorbic acid equivalents ($\mu$g of ascorbic acid/g of dry matter), using a correlation reported by Suárez et al. (22).

The antioxidant activity of the raw materials is shown in Figure 1. Apple pomace had the highest antioxidant activity at 5,390 $\mu$g of ascorbic acid equivalent/g; antioxidant activity for tomato pomace was 4,270 $\mu$g of ascorbic acid equivalent/g. Other studies have reported antioxidant activity of the same order: 6,660 $\mu$g of ascorbic acid equivalent/g for apple pomace (22) and 2,580 $\mu$g of ascorbic acid equivalent/g for tomato pomace (3). The magnitude, however, depends on the extraction method and varieties used. Antioxidant activity for whole soft wheat flour was measured at 4,460 $\mu$g of ascorbic acid equivalent/g, which was considerably lower than the previously reported range of 20,000–30,000 $\mu$g of ascorbic acid equivalent/g for various wheat cultivars after conversion from percent radical scavenging capacity (4). This was not surprising because the level of phenolics in the whole wheat flour used in this study was also much lower. However, it was intriguing that despite the much higher levels of phenolics in the pomaces compared with the wheat flour (and, in the case of tomato pomace, additional carotenoids as well), their antioxidant activities were similar. This perhaps reflects differences in the availability of the phenolic compounds to react with free radicals depending on their source and the presence of other compounds in the extracts.

Figures 2 and 3 show the antioxidant activity of low- and high-temperature (LT and HT, respectively) extruded products containing apple or tomato pomace.

Fig. 2. Antioxidant activity (AA) of unprocessed blends and low- and high-temperature (LT and HT, respectively) extruded products containing apple pomace.

Fig. 3. Antioxidant activity (AA) of unprocessed blends and low- and high-temperature (LT and HT, respectively) extruded products containing tomato pomace.

Antioxidant activity was up to 31% higher for extruded products containing apple and tomato pomaces compared with the corresponding raw material (unprocessed) blends, indicating that thermomechanical processing had a positive impact on the scavenging capacity of antioxidants present in the whole wheat flour and pomaces. Even in the absence of pomace (control), extrusion led to an increase in antioxidant activity, although the magnitude of increase (10–14%) was not as high for the control compared with the other treatments. These were significant findings because they underscore that the health-promoting activity of phytochemicals present in fruit and vegetable by-products (and not just those present in grains) can be enhanced by processing,
even when their concentrations decrease. Previous studies involving extrusion have shown either inconclusive or contrary results with respect to antioxidant activity for products incorporating blueberry, grape, cranberry, and raspberry powders (5); cauliflower, tomato, onion, and carrot powders (20); and tomato and grape pomaces (3).

Substantial differences and specific trends in antioxidant activity were not observed with respect to extrusion temperature. However, it is notable that improvement in antioxidant activity for extruded products containing apple pomace (28–31%) was more pronounced compared with those containing tomato pomace (14–15%). Although it is known that thermal processing of tomatoes leads to improvement in the free-radical scavenging capacity of carotenoids, it is primarily attributed to an increase in the pool of bioaccessible lycopene (9). A different set of mechanisms might have been at work in the current study, including additive and synergistic effects of various phytochemicals, release of unidentified phytochemicals from the matrix, and/or pressure-induced isomerization of antioxidants such as lycopene to more bioactive conformations (9,24,27). The unique low-moisture and high-pressure, shear, and temperature environment during thermo-mechanical extrusion processing may play a special role in this context.

Conclusions
Processed foods are often perceived as having negative attributes, including limited nutritional value, high calorie content, increased glycemic index, and excessive amounts of sugar, salt, chemical preservatives, and/or oil. Extrusion is a technology that is widely used for processing ready-to-eat snack and breakfast cereal products. This article describes a viable avenue for improving the nutritional profile of extruded foods by delivering both fiber and antioxidants through incorporation of fruit and vegetable by-products. In the samples tested, extrusion led to a decrease in the concentration of antioxidants (phenolic compounds and carotenoids) in expanded products containing apple and tomato pomaces. However, the free-radical scavenging capacity (antioxidant activity) increased due to processing, underscoring the potential health benefits of incorporating these ingredients. These positive aspects need to be investigated further, including the mechanism of antioxidant activity enhancement. This is part of ongoing investigations by our research group.

Acknowledgments
We thank Eric Maichel (Kansas State University) for technical assistance with this project.

References
5. Camire, M. E., Dougherty, M. P., and Briggs, J. L. Functionality of fruit powders

An ad appeared here in the print version of the journal.


23. Takeoka, G. R., Dao, L., Flessa, S., Gil-


Sajid Alavi is a professor in the Department of Grain Science and Industry at Kansas State University, Manhattan, KS. He received his B.S. degree in agricultural engineering from the Indian Institute of Technology; M.S. degree in agricultural and biological engineering from The Pennsylvania State University; and Ph.D. degree in food science/food engineering from Cornell University. His research interests include food engineering and, more specifically, the areas of extrusion processing of food and feed materials, rheology, food microstructure imaging, structure–texture relationships, and value-added uses of biological materials and residues. Sajid teaches undergraduate and graduate level courses in extrusion processing. Under his supervision, the K-State Extrusion Lab also provides extrusion training to industry professionals through short courses and services for pilot-scale trials for various products and applications. Sajid is an AACC member and can be reached at salavi@ksu.edu.

Ananda Nanjundaswamy is an assistant professor in the Department of Agriculture, Alcorn State University, Lorman, MS. He earned his B.S. and M.S. degrees in agriculture and agricultural biochemistry, respectively, from the University of Agricultural Sciences, India, and Ph.D. degree in grain science and industry from Kansas State University. Prior to his current position, he was a postdoctoral researcher at Auburn University at Montgomery and worked on a U.S. Department of Energy-funded million-dollar research project on cellulosic biofuel. Ananda has more than 15 years of bioprocessing research experience, including 8 years of industry research and manufacturing experience in bio-products such as enzymes, biopharmaceuticals, and biopesticides. His research interests include bioenergy, feedstock evaluation for biofuel production, bioprocess optimization, enzyme kinetics in biomass deconstruction, chromatography, and bioprocess scale-up. Ananda can be reached at ananda@alcorn.edu.

Ron Madl is research professor emeritus in the Department of Grain Science and Industry at Kansas State University, Manhattan, KS. He received his B.S. degree in chemistry from Baker University, Baldwin City, Kansas; M.S. degree in physical chemistry from Kansas State University; and Ph.D. degree in biochemistry from the Department of Grain Science & Industry, Kansas State University. He was employed by Protein Technologies International (now Solae) and MGP Ingredients during his 24 year industrial career. In 1997 he returned to Kansas State University, where he served as research professor and director of the Bioprocessing & Industrial Value Added Program and codirector of the Center for Sustainable Energy until he retired in 2012. His research interests continue in the area of bioactive components of cereal grains, as graduate students complete their programs under his supervision. Ron is an AACC member and can be reached at mdal@ksu.edu.

Praveen Vadlani is the Gary and Betty Lortscher Associate Professor in Renewable Energy in the Department of Grain Science and Industry Department at Kansas State University, Manhattan, KS. He received his B.S. degree in chemical engineering from the National Institute of Technology Karnataka, India; M.S. and Ph.D. degrees in biochemical engineering from the Indian Institute of Technology; and MBA from Kansas State University. Prior to his academic career, Praveen worked in the biopharmaceutical and biofuels industries for 12 years. He has considerable expertise in biocatalysis and fermentation related to industrial and specialty chemicals from renewable resources. Praveen has conducted research and taught at the University of Malaya, Malaysia; University of Auckland, New Zealand; Texas A&M University; and Sri Sathya Sai Institute for Higher Learning, India. Praveen can be reached at vadlani@ksu.edu.